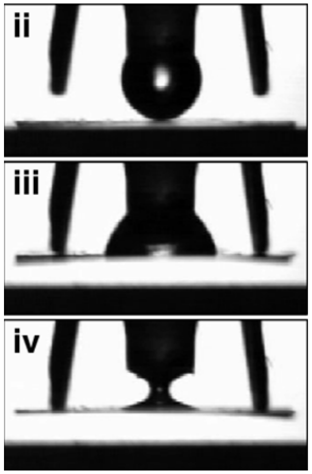
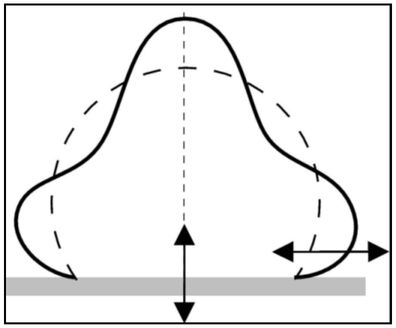
Wetting, spreading & capillary adhesion: putting shape-instability to purpose





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NSF
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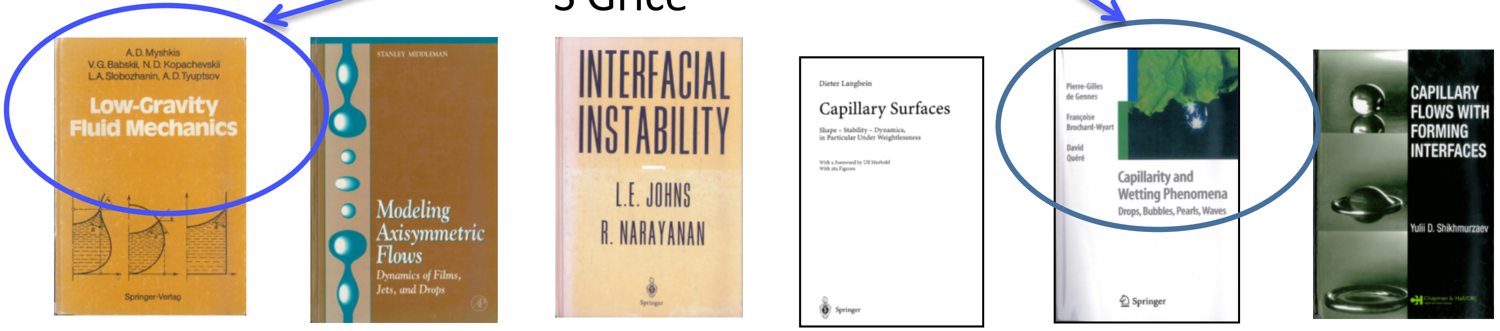
S Grice



as Mother Nature teaches !

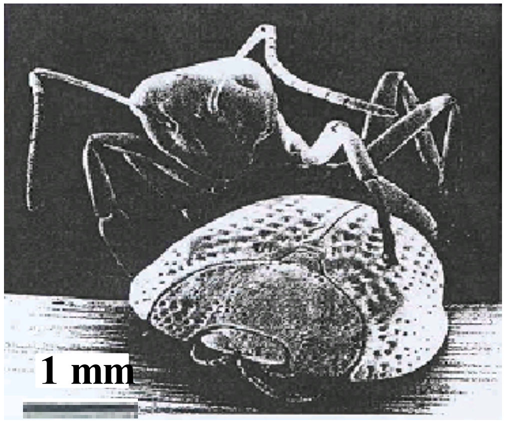
Eisner & Aneshansley, "Defense by foot adhesion in a beetle",
PNAS 97(12) 2000

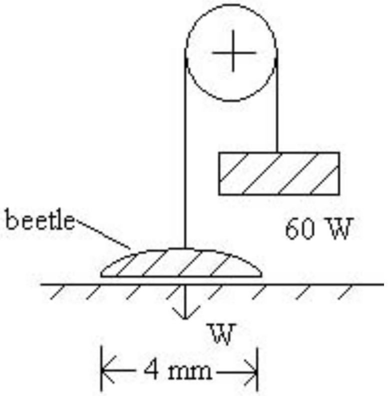
BBC 'Secret Weapons'

the beetle's feat

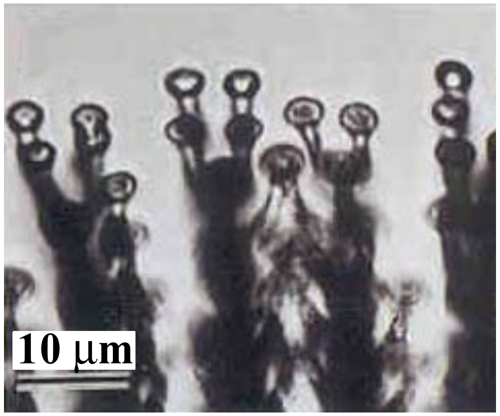
Eisner & Aneshansley, "Defense by foot adhesion in a beetle",
PNAS 97(12) 2000

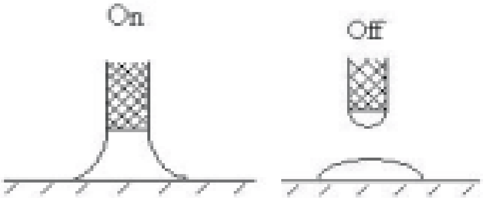
attack

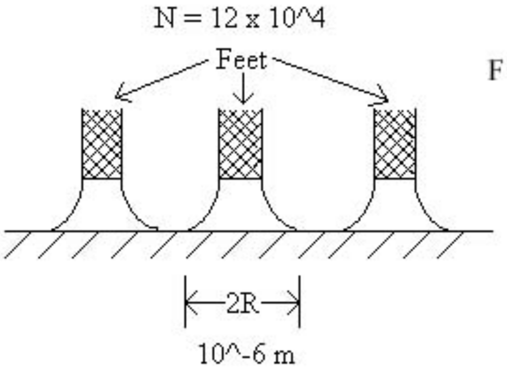




defense

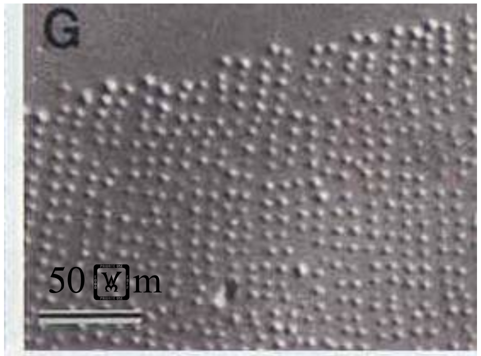






F ~ N (2πR)σ
~ 10^3 dyne

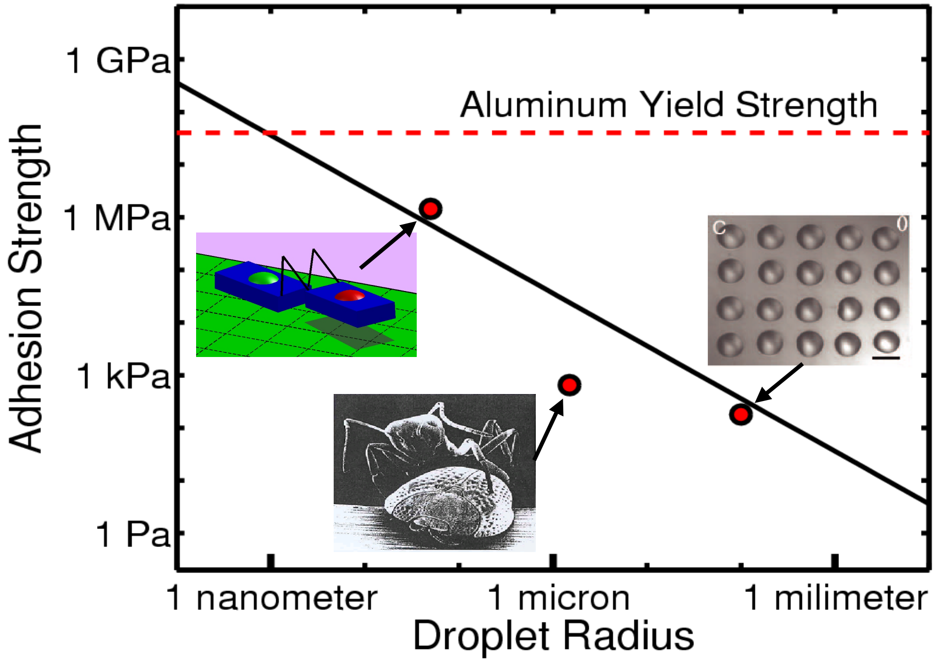
surface tension



$$F = \sigma\{2\pi R \sin(\alpha_0) + \pi R^2(\kappa_1 + \kappa_2)\}$$

favorable scaling

$$Adhesion\ Strength \propto \frac{1}{Droplet\ Radius}$$

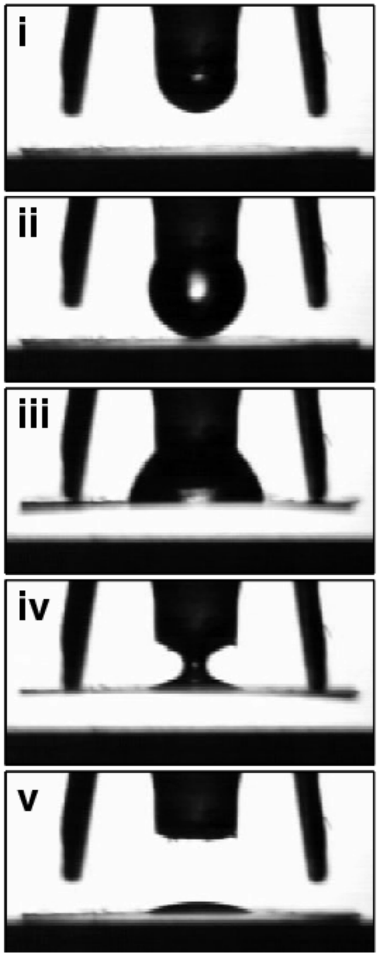


$$F \sim (\ell/R)\sigma\ell$$

macroscale

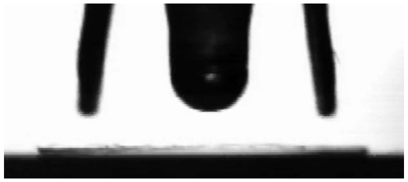
Q. a man-made device based on perimeter-packing?

grab/release concept



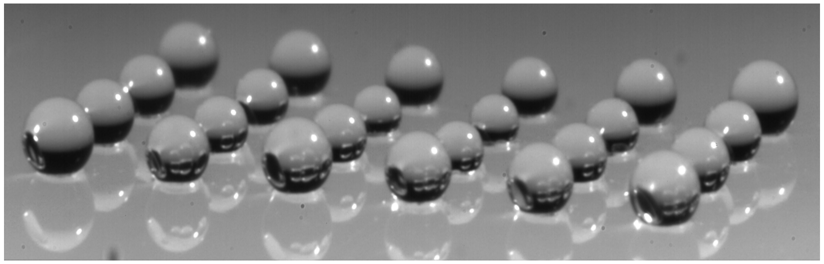
1.7 mm tube diameter

Aluminum foil

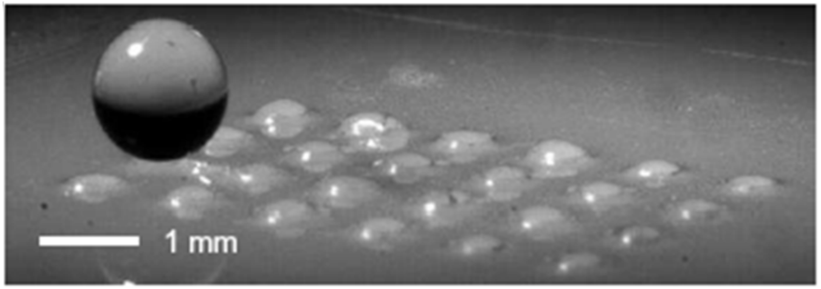


lab demo

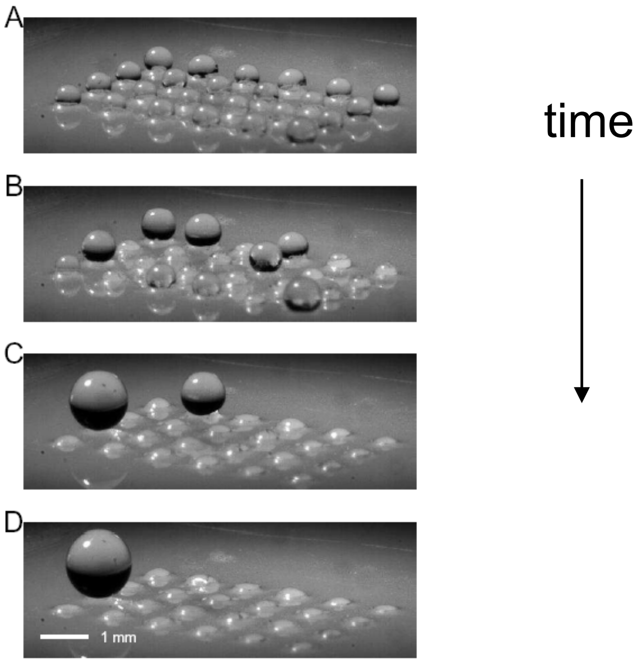
capillary coarsening



initial

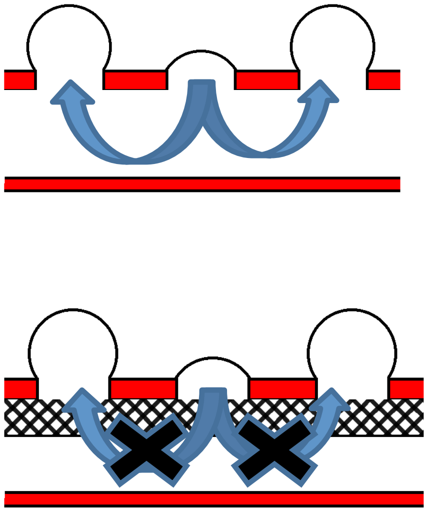


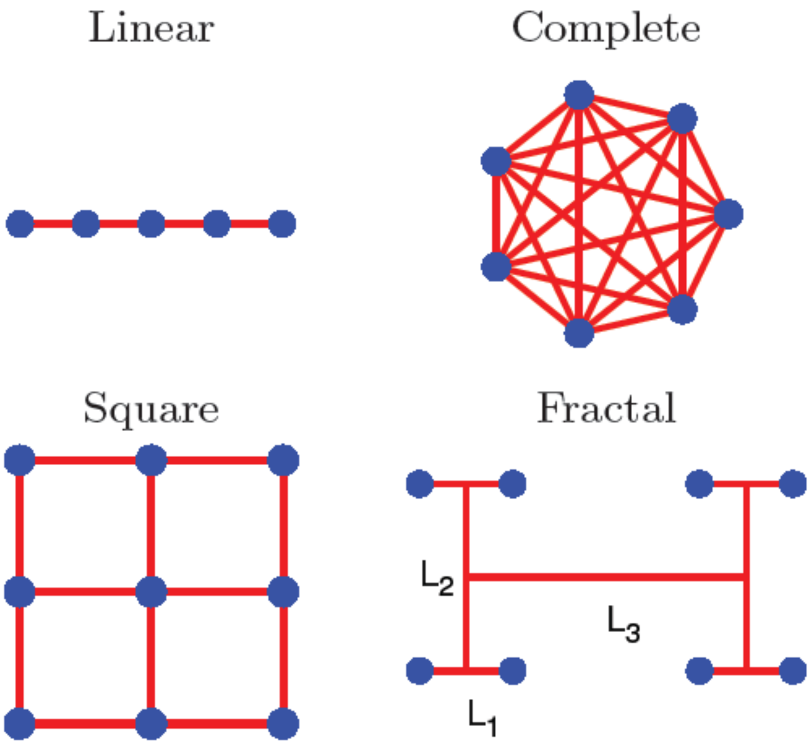
final - equilibrium



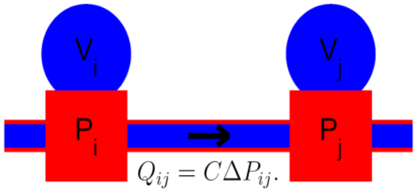
van Lengerich, Vogel, PHS, PRE

Q. can passive design mitigate coarsening?





dynamical-system

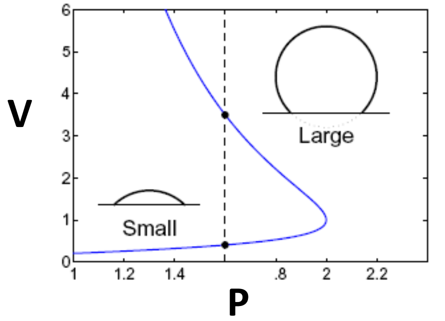


$Q_{ij} = C\Delta P_{ij}.$

Hagen-Poiseuille

viscosity resists

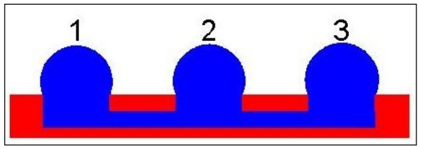
spherical-cap response



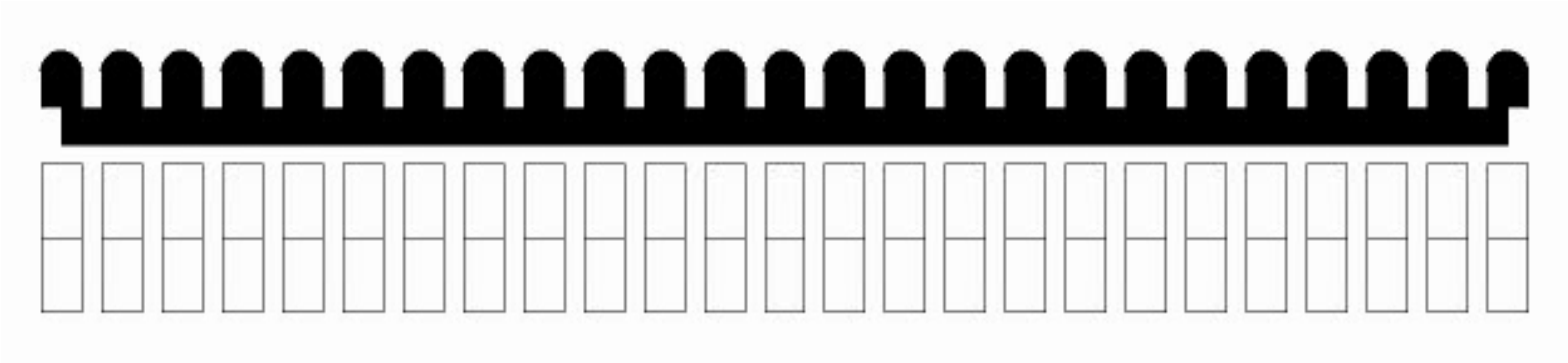
$$\frac{dV_1}{dt} = c_{21}\ \Delta p_{21}, \qquad V_1(0) = V_{10}$$

$$\frac{dV_2}{dt} = c_{12}\ \Delta p_{12} + c_{32}\ \Delta p_{32}, \qquad V_2(0) = V_{20}$$

$$\frac{dV_3}{dt} = c_{23}\ \Delta p_{23}, \qquad V_3(0) = V_{30}.$$



$$\sum_{j=1}^{N} V_j = const.$$



Chandrasekhar

Jacobi

Newton

Euler

Liouville

Poincare

coarsening rates

$\dot{V}_L = c\Delta P_L$

Equation for pressure $P_L \sim 1/r \sim 1/V_L^{1/3}$ Thus $\dot{V}_L = cV_L^{-1/3}$

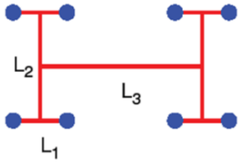
Total number of large drops $N_L \sim 1/V_L$

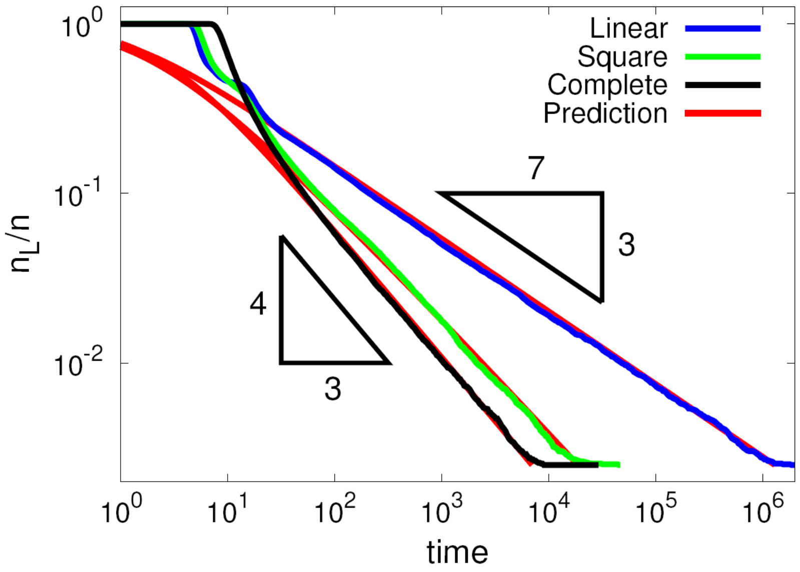
$c \sim 1$

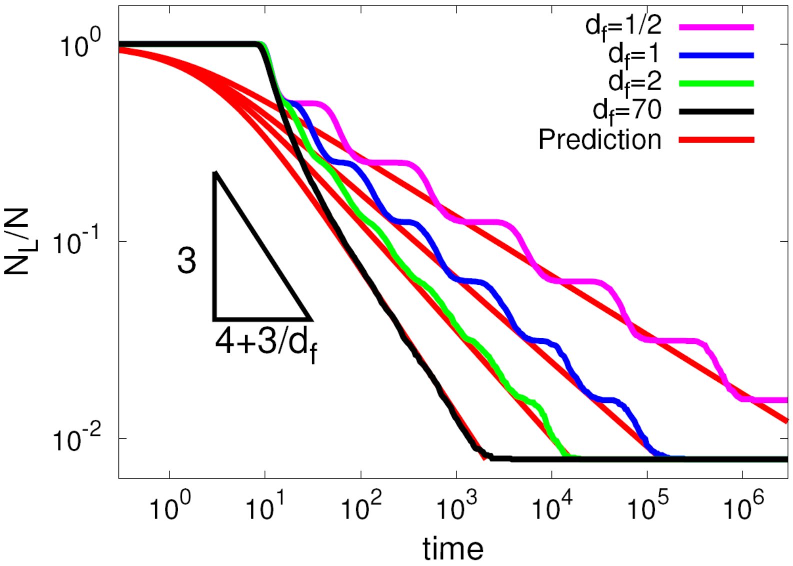
$N_L \sim t^{-3/4}$

$c \sim N_L \sim 1/V_L$

$N_L \sim t^{-3/7}$



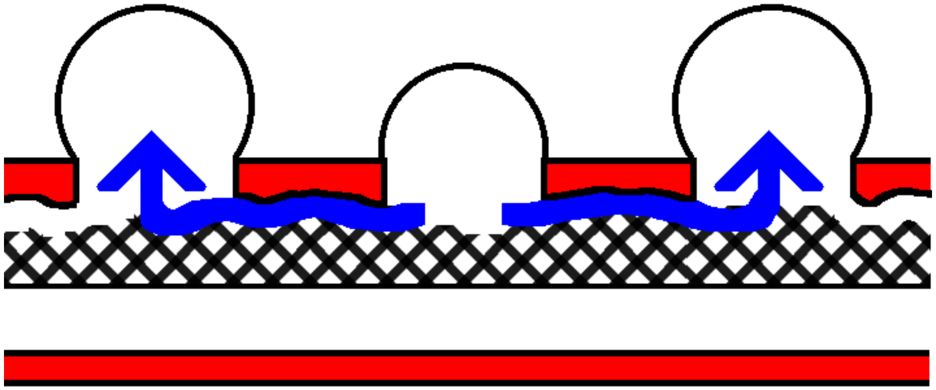




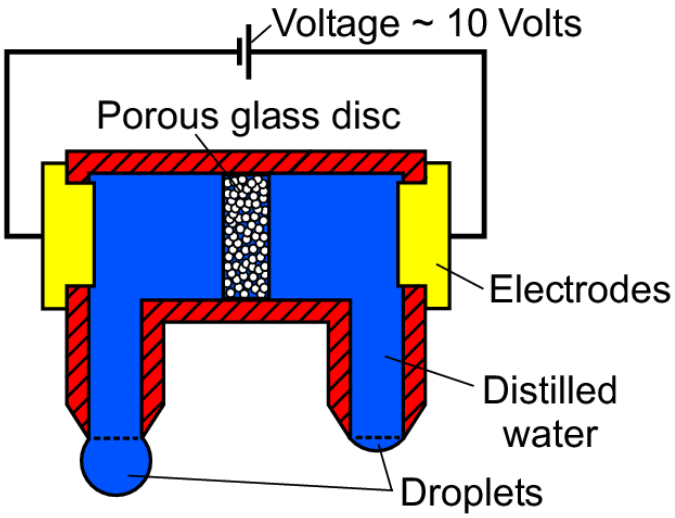
capillary coarsening recap

- neighbors compete, self-similarity

- no ‘signature’ for defective pads



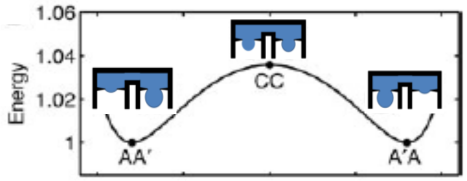
Q. how to make switchable (active)?

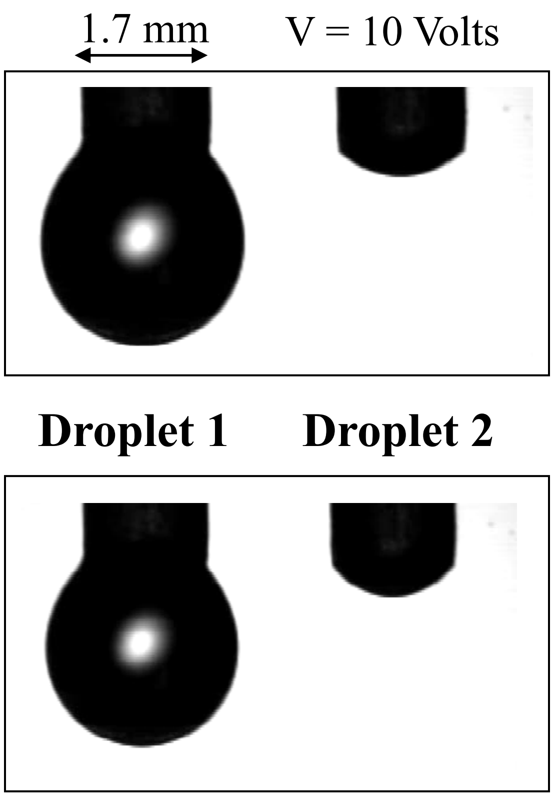


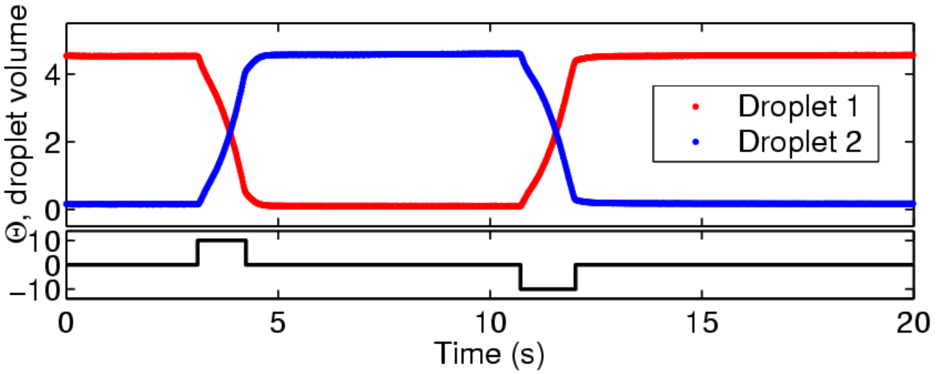
A. electro-osmotic pumping

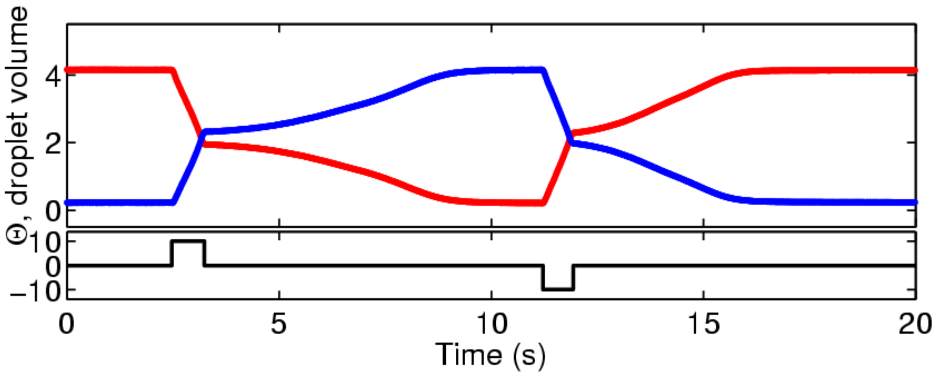
e.g. Zeng, S, Chen, C.-H, Mikkelson, J. C. & Santiago, J. G. (2001)

probing the barrier



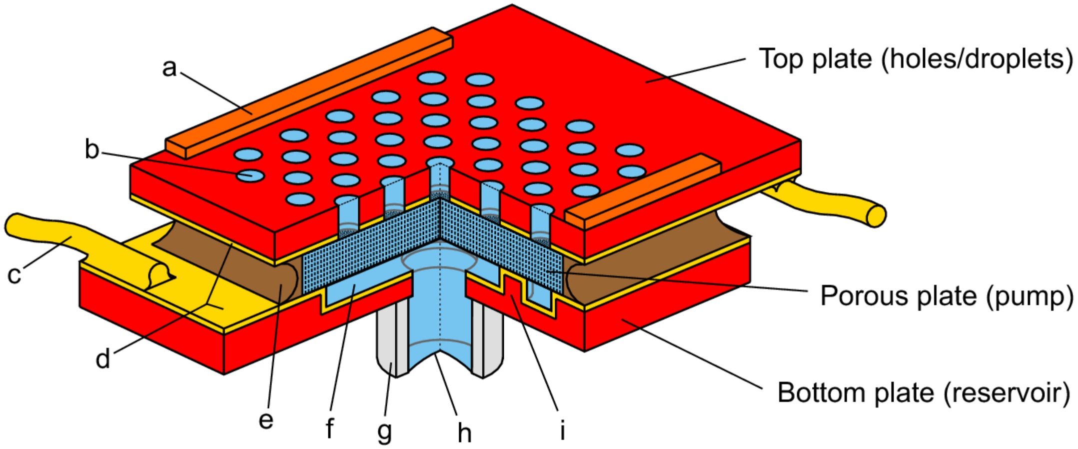




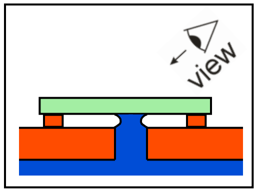


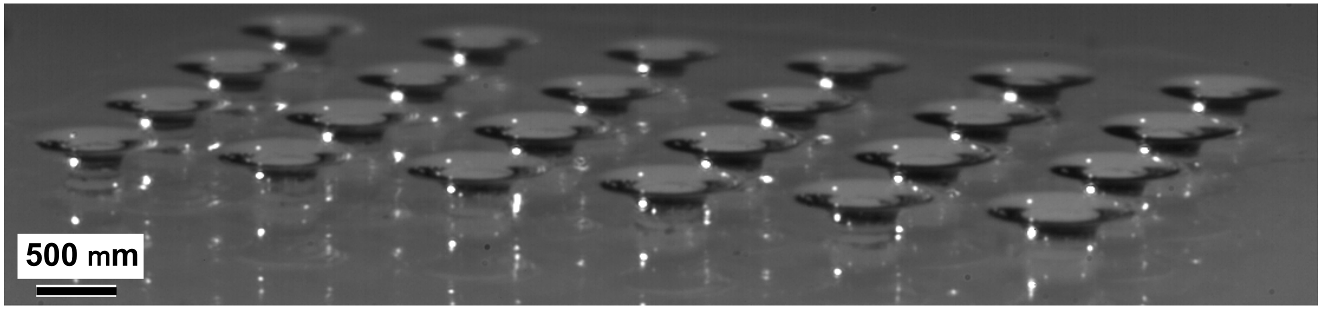
PHS, Vogel, Ehrhard, Proc Nat Acad Sci, 2005.

adhesion device

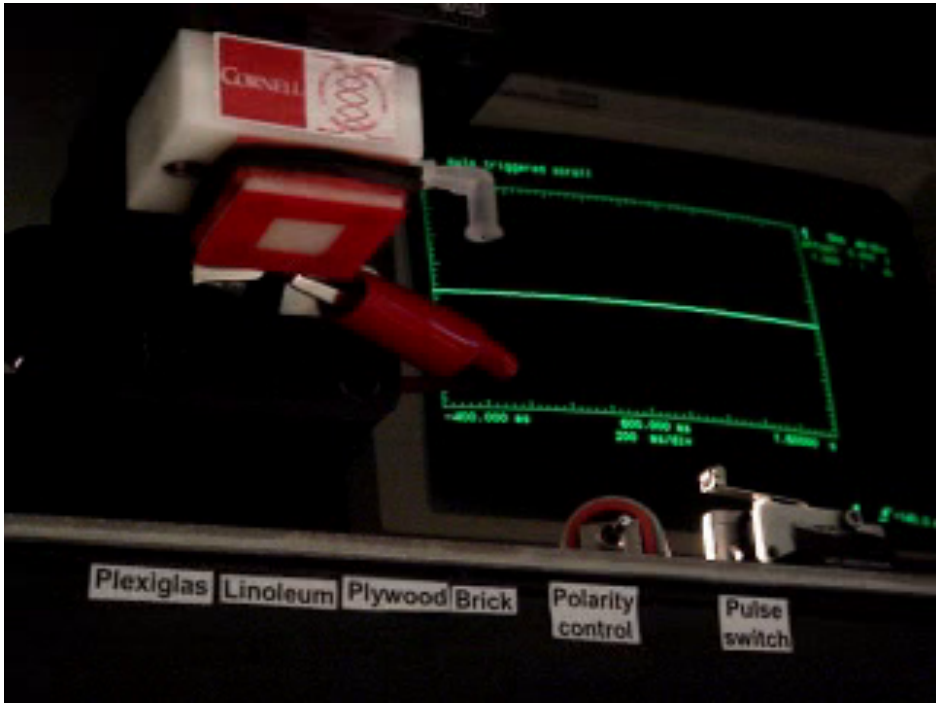


Vogel, PHS, Proc Nat Acad Sci, 2010.





big-mac device performance



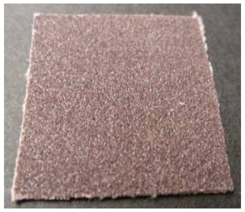
shown
tested here

Linoleum: 700 mg

Plywood: 725 mg

Brick: 670 mg

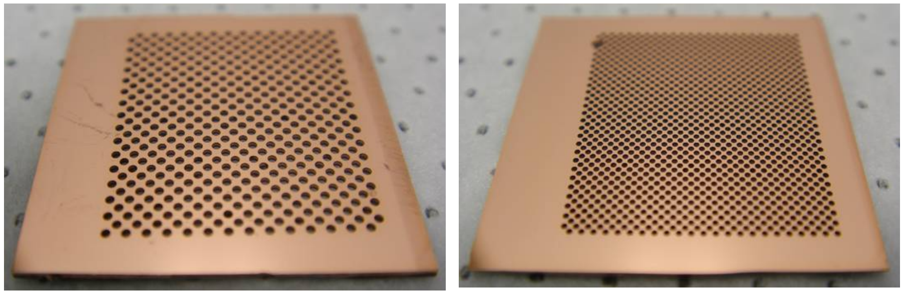
also tested successfully



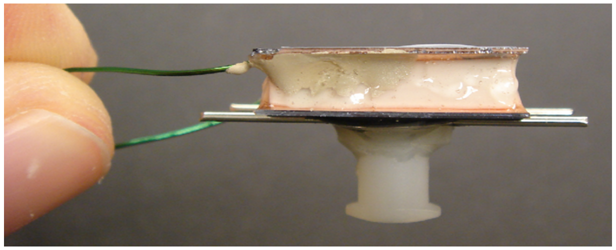
Sandpaper (150 grit): 650 mg

Roof shingle: 675 mg

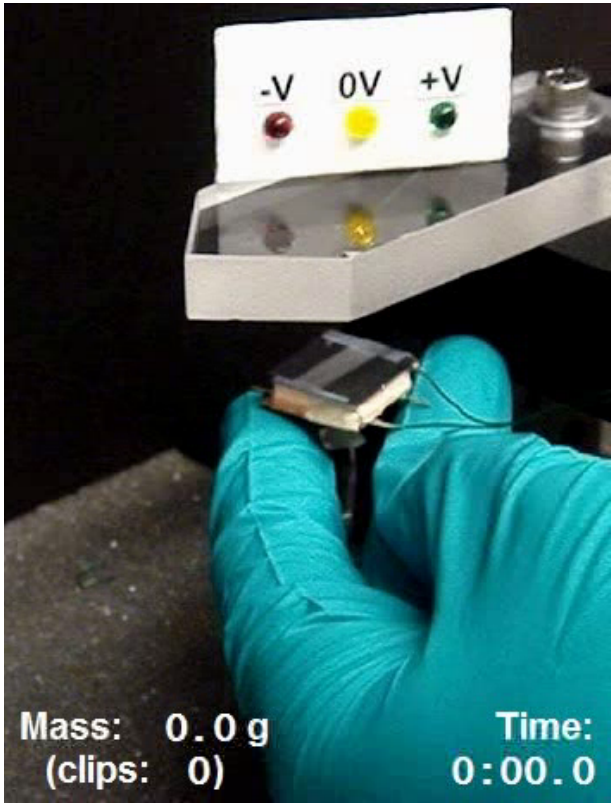
silicon-wafer device



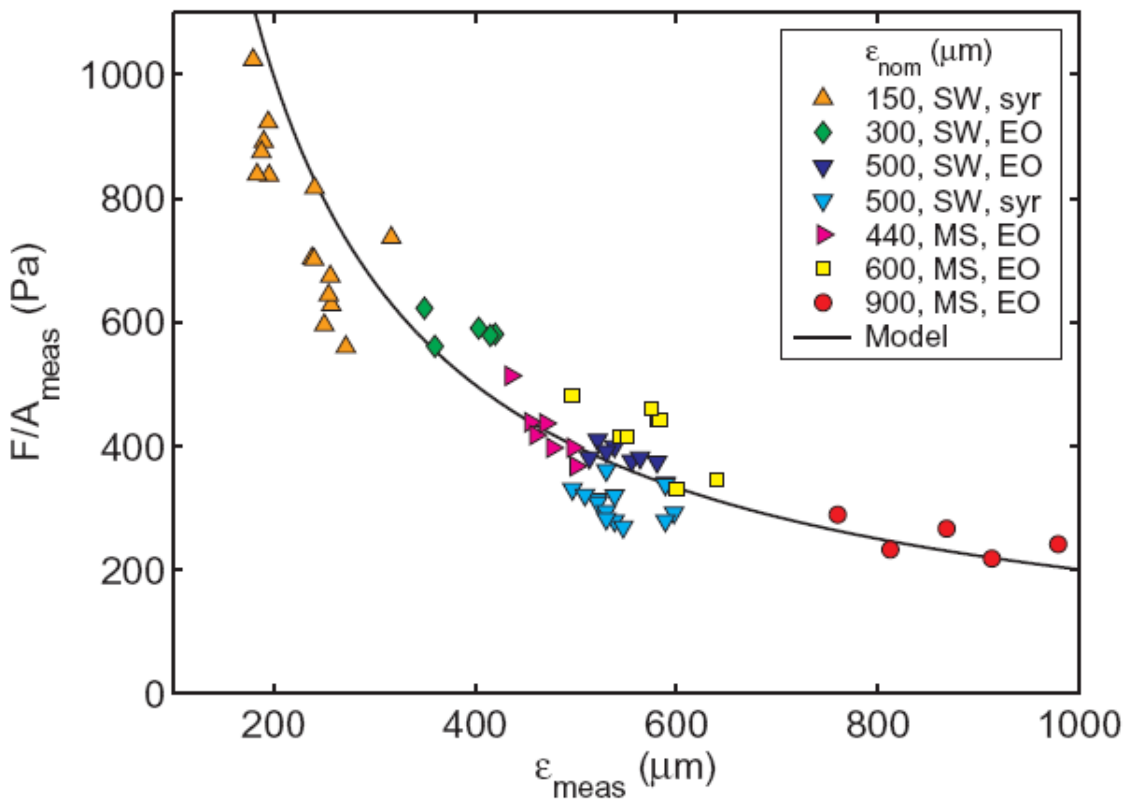
e = 500, 300 (or 150 mm)

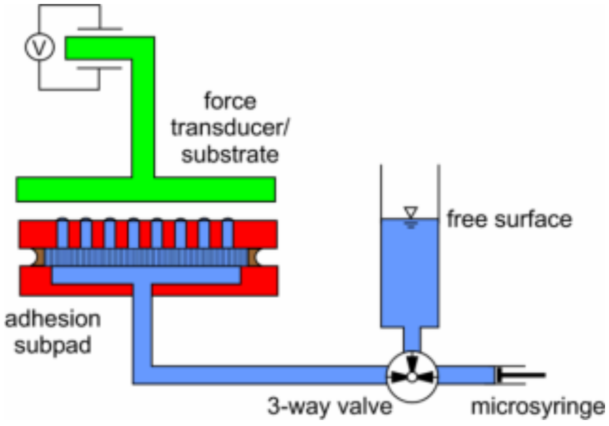


Glass frit pump
(device thickness ~ 5 mm, mass ~ 4 g)



average force measure

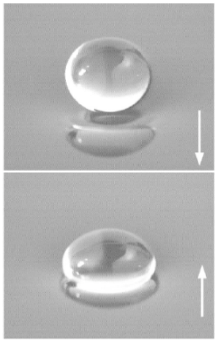




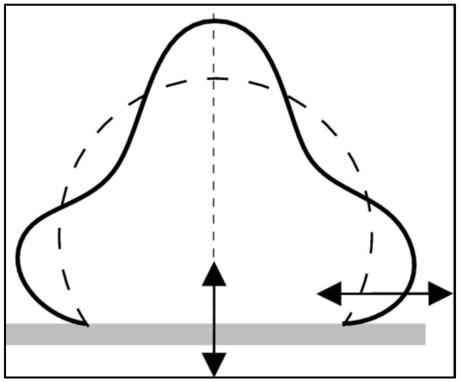
A. perimeter-packing achieved!

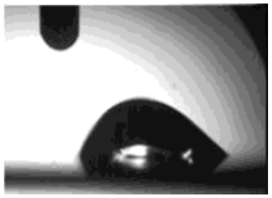
Vogel, PHS, Proc Nat Acad Sci, 2010.

droplet manipulation



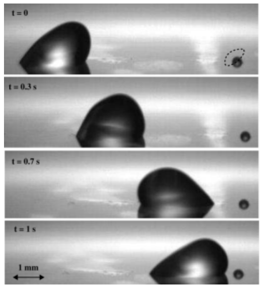
Couder et. al 05





Daniel et. al 04

Smith et. al 2007



Noblin et. al 09

Q. natural frequencies?

literature

Theory

Strani & Sabetta *(84, 88)*

Ganan & Barerro *(90)*

Bauer & Chiba *(04, 05)*
Lyubimov *et al. (04, 06)*

Fayzrakhmanova & Straube (09)

Computation

Basaran & DePaoli, 94

DePaoli *et al. (95)*
Wilkes & Basaran, 01
James *et al. (03)*

Experiment

Rodot *et al. (1979)*
James *et al. (03)*
Daniel *et al. (04)*
Noblin *et al. (04)*

Couder et. al *(05)*

Vukasinovic *et al. (07)*
Brunet *et al. (09)*

Rayleigh oscillations

surface tension

$$\omega_k^2 = k(k-1)(k+1)(k+2)\frac{\sigma}{\rho r^3} \qquad k = 0, 1, 2, \ldots$$

liquid density

sphere radius

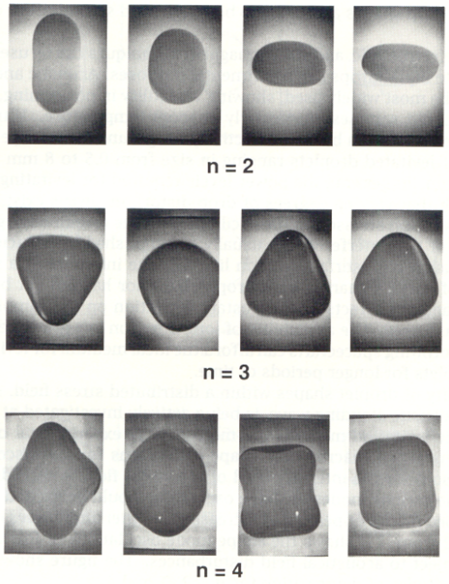
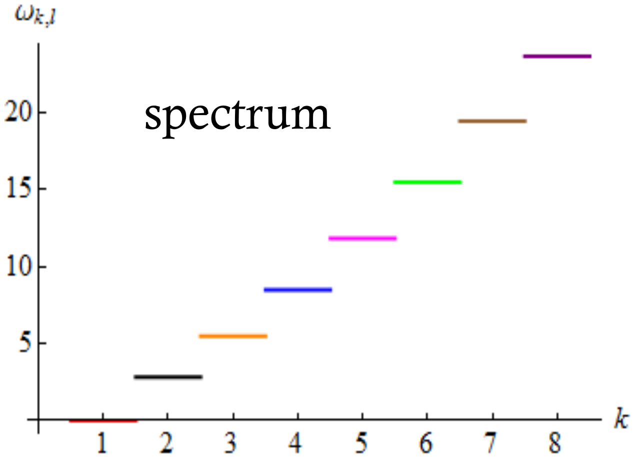
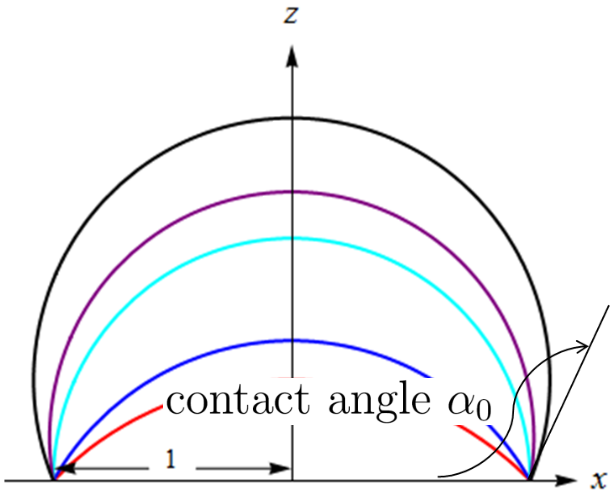
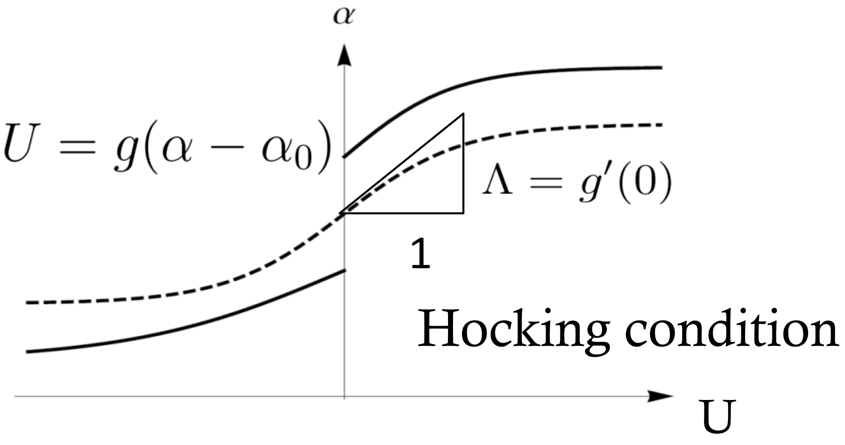


Figure 6.2 Photographs of the shape modes of oscillations for liquid drops suspended in another liquid for modes n = 2, 3, and 4, from [71]. *Courtesy E. H. Trinh.*



spherical-cap base-state w/ ‘Hocking’ spreading





$$0 < \alpha_0 < \pi$$

$$\boxed{0 \le \Lambda < \infty}$$

mobile

pinned

Hocking, JFM 1977
Davis, JFM 1980

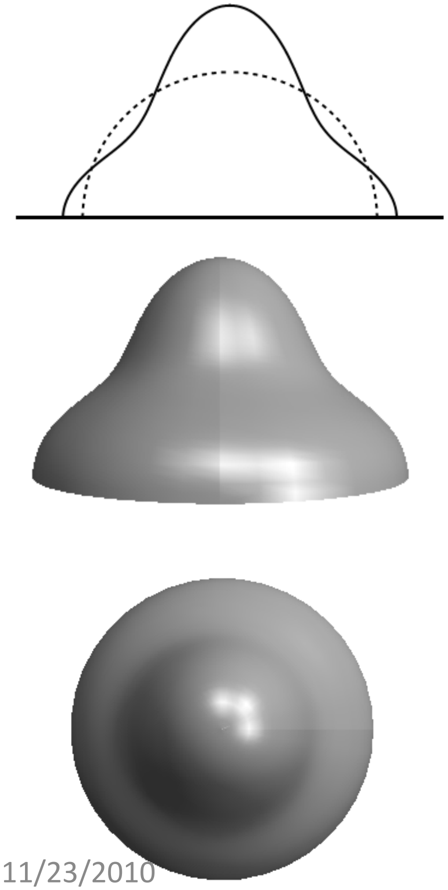
classify mode shapes

$$\eta(s,\varphi,t) = y(s)\mathrm{e}^{i\omega t}\mathrm{e}^{il\varphi}$$

$$k,l = polar, azimuthal \quad wavenumber$$

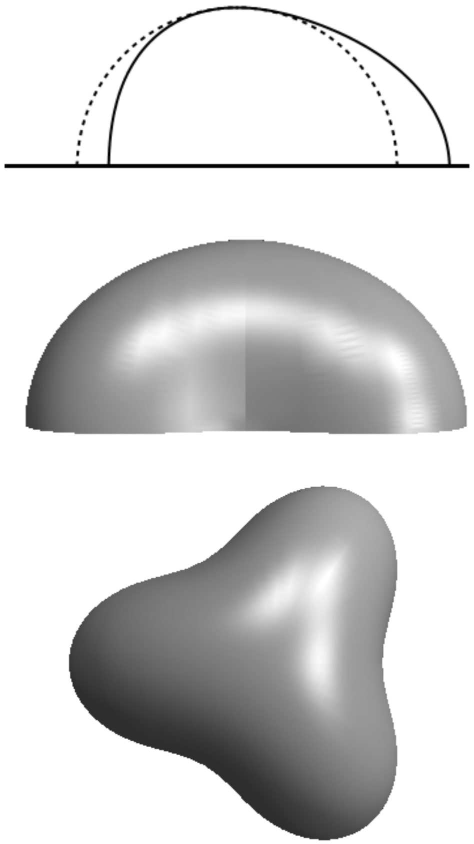
$Zonal \quad l = 0$

$k,l = 4,0$



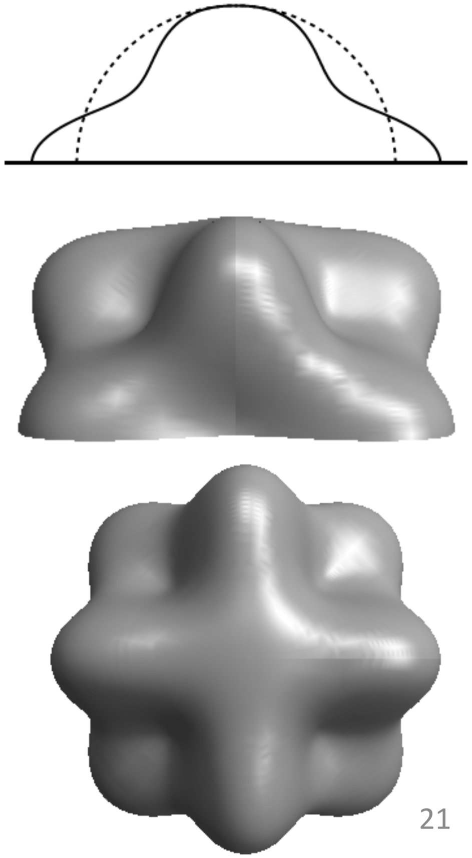
$Sectoral \quad l = k$

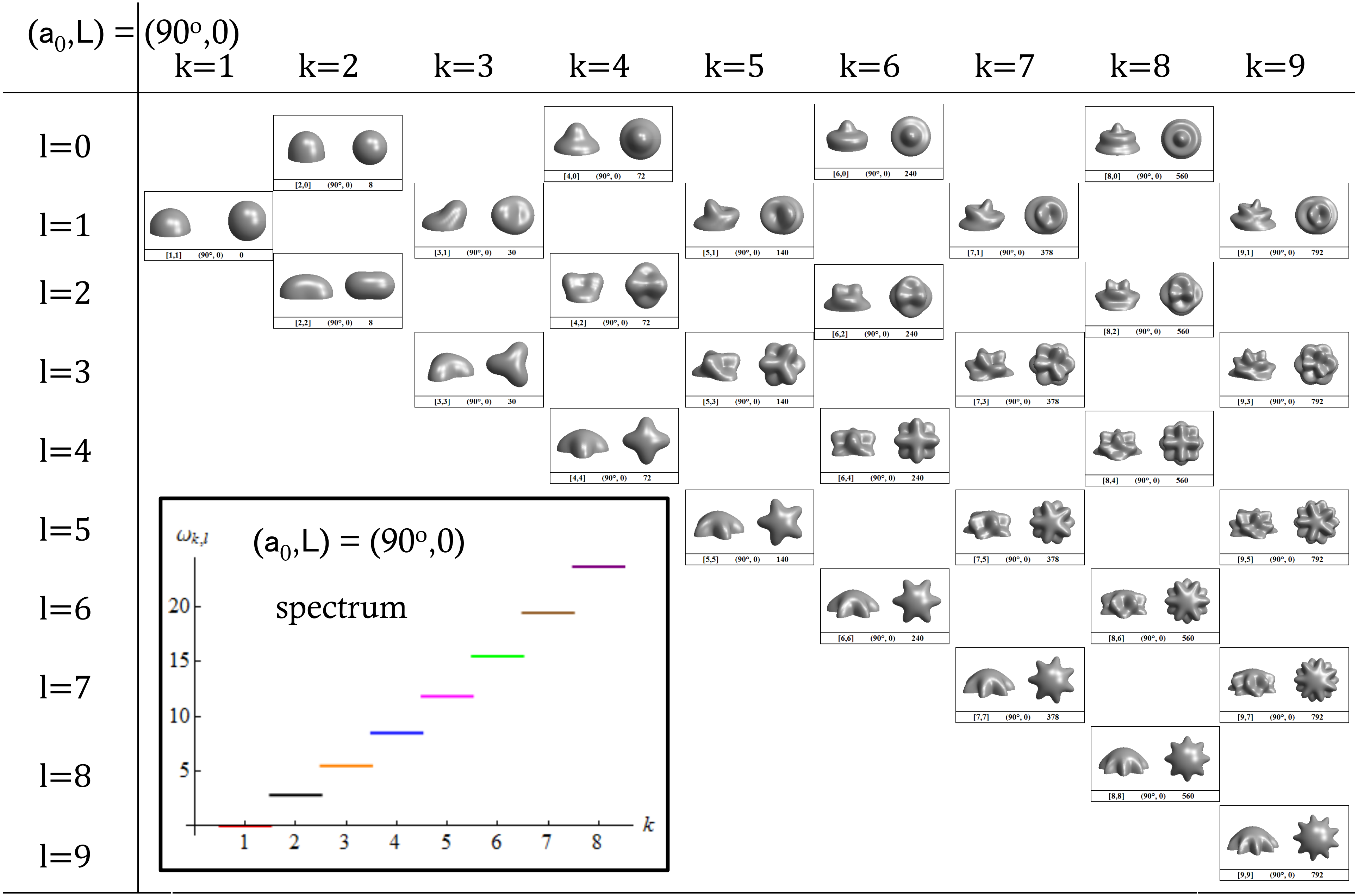
$k,l = 3,3$



$Tesseral \quad l \neq k$

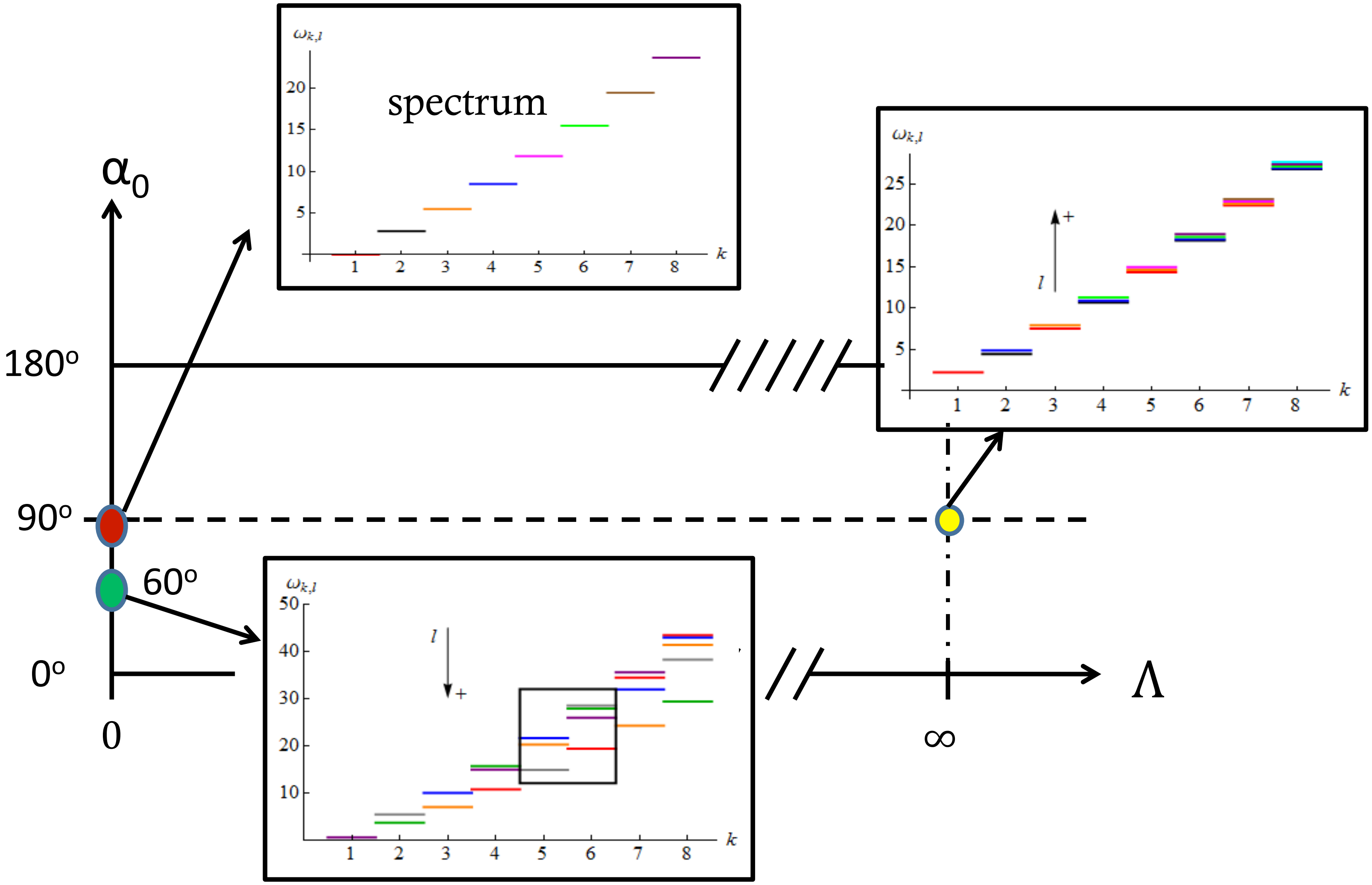
$k,l = 6,4$





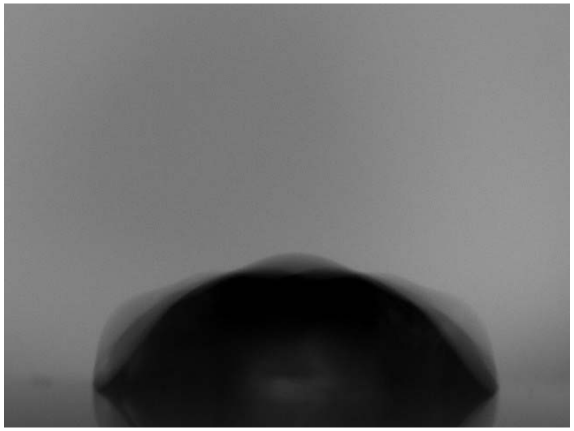
classify mode shapes

unfolding of spectra



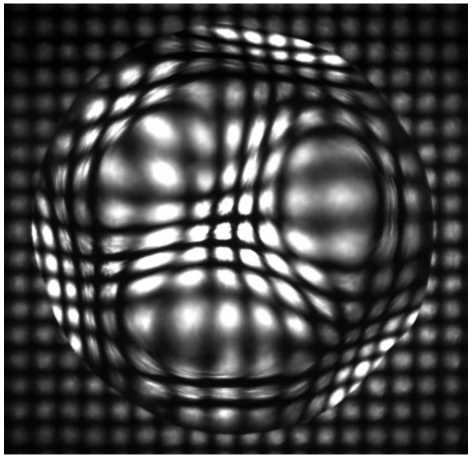
sessile-drop recap

- spectra split for $(\alpha_0, \Lambda) \neq (90^\circ, 0)$
- damped (effective dissipation) for $\Lambda \neq 0, \quad 1/\Lambda \neq 0$



side

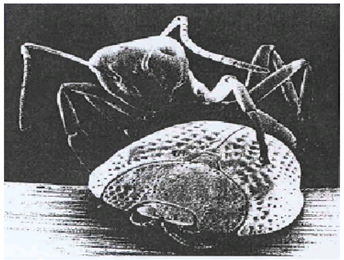
[3,3] mode



top

concluding remarks

- beetle lessons
  - perimeter-packing, switchable



- coarsening & coalescence mitigation
  - passive design

- grab-release device w/ eo pump
  - perimeter-packing, switchable adhesion
- sessile-drop oscillations
  - spectral splitting